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FACULTY OF MECHATRONICS, INFORMATICS
AND INTERDISCIPLINARY STUDIES

N2612 – Electrical engineering and informatics
2612T071 – Engineering of Interactive Systems

**RESIDENTIAL HEAT RECOVERY UNIT**

**CONTROLLED BY PLC**

DIPLOMA THESIS

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# Zadání diplomové práce

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1. Familiarize with the system of the residential heat recovery unit of Atrea Company controlled by Foxtrot PLC system.
2. Design and develope control program for recuperation using CO2 sensors.
3. Apply this program in the real system in the laboratory.
4. Analyze possibilities to use CO2 sensors to sense presence of number of persons in the room.

**Seznam odborné literatury** (text nijak neformátujte, pouze každou položku uveďte jako nový odstavec)**:**


Pavel Ripka and Alois Tipek, editors. Master Book on Sensors: Modular Courses on Modern Sensors – Leonardo da Vinci project CZ/PP – 134026. Number Part A. BEN: Praha, 2003. ISBN 80-7300-129-2.

Pavel Ripka and Alois Tipek, editors. Master Book on Sensors: Modular Courses on Modern Sensors – Leonardo da Vinci project CZ/PP – 134026. Number Part B. BEN: Praha, 2003. ISBN 80-7300-129-2.

Bolton W. Programmable Logic Controllers. Elsevier, 5. edition, 2009. ISBN 978-1-85617-751-1.


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// Abstract

The topic of this diploma thesis is recuperation unit controlled by programmable logic controller. The recuperation unit is a technology used for heating of objects. The control is realised by the programmable logic controller (PLC). The PLC is watching data from temperature sensors and sensors of $CO_2$ concentration. This data are used by PLC for controlling the temperature and the freshness of the air in an object as user needs. The recuperation unit ATREA DUPLEX RB is presented in this thesis. Also the other components required for good working of the whole system are presented in this thesis. The other components are residual-current device, DC power supply, variable-frequency drives for controlling of the asynchronous electric motors, NDIR sensors of the $CO_2$ concentration, temperature sensor Ni1000. The automatic control is realised by the PLC TECOMAT FOXTROT CP-1018. Last part of this thesis is focused on using $CO_2$ concentration sensors for the estimation of the number of persons in the given room.

## Keywords

Recuperation unit, programmable logic controller (PLC), Mosaic, WebMaker, NDIR sensor

// Abstrakt

Téma této diplomové práce se týká rekuperační jednotky řízené programovatelným logickým automatem.

Rekuperační jednotka je technologie používaná pro vytápění objektů. Řízení rekuperační jednotky je realizováno programovatelným logickým automatem (PLC). PLC vyhodnocuje informace z teplotních čidel a čidel sledujících hladinu $CO_2$ . Na základě těchto informací ovládá ventilátory a klapky rekuperační jednotky. PLC tak řídí teplotu a čerstvost vzduchu v objektu podle potřeb uživatele. V této práci je představena rekuperační jednotka ATREA DUPLEX RB. Jsou představeny i ostatní komponenty potřebné pro zajištění správného chodu celého systému. Těmito komponentami jsou jističe, zdroj stejnosměrného napětí, frekvenční měniče pro ovládání asynchronních motorů, NDIR čidla koncentrace $CO_2$, teplotní čidla Ni1000. Automatické řízení je realizováno PLC TECOMAT FOXTROT CP-1018.

Poslední část této práce je zaměřena na možnosti využití čidel koncentrace $CO_2$ k odhadu počtu osob nacházejících se v dané místnosti.

// Klíčová slova

Rekuperační jednotka, programovatelný logický automat (PLC), Mosaic, WebMaker, NDIR čidlo

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# List of abbreviations

| | |
|---|---|
| MC | ventilator of the circulation |
| MV | ventilator of the waste air |
| DAC | damper of the circulation |
| DAO | damper out |
| BP | by-pass |
| HU | heating unit |
| T_MV | temperature sensor Ni1000 of the ventilator of the waste air |
| T_MC | temperature sensor Ni1000 of the ventilator of the circulation |
| T_INT | temperature sensor Ni1000 inside the room |
| T_OUT | temperature sensor Ni1000 outside |
| S1 | NDIR sensor ASC$O_2$-GD in the circulation pipe |
| S2 | NDIR sensor ASC$O_2$-GD in the circulation pipe |
| c1 | input of the circulation air from the object to the recuperation unit |
| c2 | output of the circulation air from the recuperation to unit the object |
| e1 | input of the fresh air from outside to the recuperation unit |
| i1 | input of the waste air from the object to the recuperation unit |
| i2 | output of the waste air from the recuperation unit to the outside |

# 1 Introduction

This diploma thesis presents the residential recovery unit which is controlled by programmable logic controller.

The residential recovery unit also called the recuperation unit is a manner of heating in objects. The basic idea of this technology is an exchange of thermal energy between waste air, which leaves the object, and fresh air, which comes into the object. For this technology is necessary to have perfectly isolated object. It means that the air flow has to pass only through the recuperation unit. These objects are called passive houses. The technology of the recuperation unit is very effective in passive houses.

For the right function of the recuperation unit is necessary to have control. The control is possible to realise by the programmable logic controller (PLC). In this thesis PLC obtains data from temperature sensors and sensors of $CO_2$ concentration in the air. This data are used by PLC for controlling the temperature and the freshness of the air in an object as user needs.

The recuperation unit ATREA DUPLEX RB produced by Czech company ATREA s.r.o. is presented in this thesis (see [2]). This device is installed in A-TK3 laboratory at Technical University of Liberec. Also the other components required for good working of the whole system are presented in this thesis. The other components are residual-current device, DC power supply, variable-frequency drives for controlling of the asynchronous electric motors, NDIR sensors of the $CO_2$ concentration, temperature sensor Ni1000.

The automatic control is realised by the PLC TECOMAT FOXTROT CP-1018 produced by Czech company Teco a.s. (see [3]). The code of the automatic and manual mode presented in this thesis is written in ST (Structured text) and developed in development environment Mosaic (also produced by Teco a.s.). One part of the Mosaic development environment is called WebMaker. The graphical visualization of the input/output data of the PLC is realised in the WebMaker. Remote control through the web interface is also realised in WebMaker. All of this is applied on the real system of the recuperation unit ATREA DUPLEX RB, which is installed in A-TK3 laboratory at Technical University of Liberec.

Last part of this thesis is focused on possibilities of using $CO_2$ concentration sensors for the estimation of the number of persons, which are in the given room. The measurement of the relation between the number of persons and the $CO_2$ concentration is realised in the A-TK3 laboratory. The course and result of this measurement is also presented in this thesis.


**Figure 1: Recuperation unit ATREA DUPLEX RB installed in A-TK3 laboratory**

In Figure 1 it is shown how does the system of the recuperation unit ATREA DUPLEX RB which is installed in A-TK3 laboratory at Technical University of Liberec look like. The power source and control system are placed in the rack bellow.

# 2 Recuperation unit of the air

The recuperation of the air is modern manner of heating systems in passive houses as was mentioned in the introduction. Passive houses are objects, which are perfectly isolated. There is a minimal exchange of the energy between inside and outside of the object. That means that energy consumption per year is very low, so it is economically attractive. The main air flow goes through the recuperation unit. Other sources of the air exchange are minimized in the passive houses. The main idea of the recuperation unit is that the thermal energy of waste air, which leaves the house, is used for heating of fresh air incoming to house. This primary process is realized in the exchanger. The exchanger can use almost 90 % of thermal energy of the waste air. It means that the recuperation is very ecological, because it saves a lot of heating energy. The condition for this is to have perfectly isolated house. Next useful functions are: cleaning air by filters and outflow of smells from the house (more information you can find in literature [1], [2], [12], [14]).

## 2.1 Producers of recuperation units

There are a lot of producers offering solutions with a recuperation unit. Mostly these companies are from air-conditioning industry. They offer complete service from the design to the installation. Sometimes it is possible to find a company which has extended service. These companies offer the design and the realization of the passive house where the recuperation unit is installed.

### 2.1.1 ATREA s.r.o.

The Czech company ATREA s.r.o. was found in 1990. The basic principle of their production is decreasing the energy consumption of air-conditioning systems by using of modern recuperation exchangers, regulation and full-automatic. The production of this company is divided to five divisions. These divisions are ventilations and recuperation units, ventilations for kitchens, ventilations and air heating for family houses or flats, measuring and regulation, building of family passive houses. The recuperation unit ATREA DUPLEX RB (in Figure 2) which is used in this thesis is a product of this company (see web [2]).

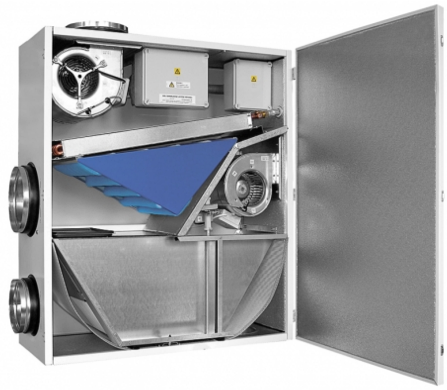

**Figure 2: ATREA DUPLEX RB [16]**

### 2.1.2 Paul Wärmerückgewinnung GmbH

The German company Paul Wärmerückgewinnung GmbH was found in 1993. This company is specialised in producing of recuperation units and supporting components for that. The company produces regulation and automatic systems for their products. The assembling is realised by external companies which are trained and certificated by this company. These companies are also in the Czech Republic (see web [12]). In Figure 3 it is possible to see the recuperation unit Santos (F) 570 DC, one of many products of the company Paul Wärmerückgewinnung GmbH (see web [17]).

**Figure 3: Recuperation unit Santos (F) 570 DC [17]**

### 2.1.3 NILAN s.r.o.

NILAN s.r.o. is the Czech subdivision of the Danish company Nilan A/S which was found in 1974. The products of this company are ventilating systems, recuperation units and heating pumps. This company provides complete service from production to final installation (for more information see web [14]). Nilan Comfort 600 [18] from NILAN Company is shown in Figure 4. It is the recuperation unit with high-performance.

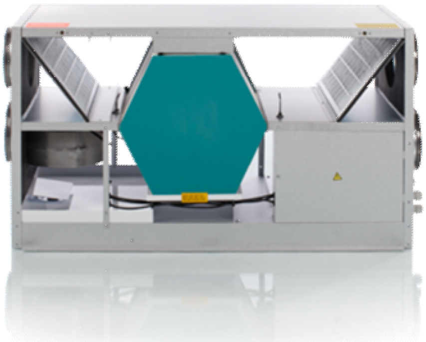

**Figure 4: Nilan Comfort 600 [18]**

In Table 1 it is possible to see comparison of presented products in this section (see also [16], [17], [18]).

**Table 1: Product comparison by volume of air circulation and price**

| Type of recuperation unit | Volume of air circulation [$m^3/h$] | Price [€] |
|---|---|---|
| ATREA DUPLEX RB | 730 | 2200 |
| Santos (F) 570 DC | 570 | 3140 |
| Nilan Comfort 600 | 600 | 2870 |

## 2.2 ATREA DUPLEX RB

The recuperation unit ATREA DUPLEX RB is presented in this thesis. This model is produced by the Czech company ATREA s.r.o. It is installed in A-TK3 laboratory at Technical University of Liberec. More details about ATREA DUPLEX RB are presented bellow. In Table 2 it is possible to see basic information about the recuperation unit ATREA DUPLEX RB like the volume of the circulation air, the efficiency, the size, the weight, the voltage and the capacity (for more information see [19]).

**Table 2: Basic parameters of the recuperation unit [19]**

| | | |
|---|---|---|
| Circulation of the air | $m^3/h$ | 730 |
| Waste air | $m^3/h$ | 440 |
| Maximal efficiency of recuperation | % | 90 |
| Height | mm | 350 |
| Depth | mm | 855 |
| Width | mm | 965 |
| Weight | kg | 74 |
| Voltage | V | 230 |
| Maximal capacity of heater | W | 3600 |

In Figure 5 the components of the recuperation unit are pointed: ventilator of the circulation (MC), ventilator of the waste air (MV), damper of the circulation (DAC), by-pass (BP), heating unit (HU), exchanger and filter.

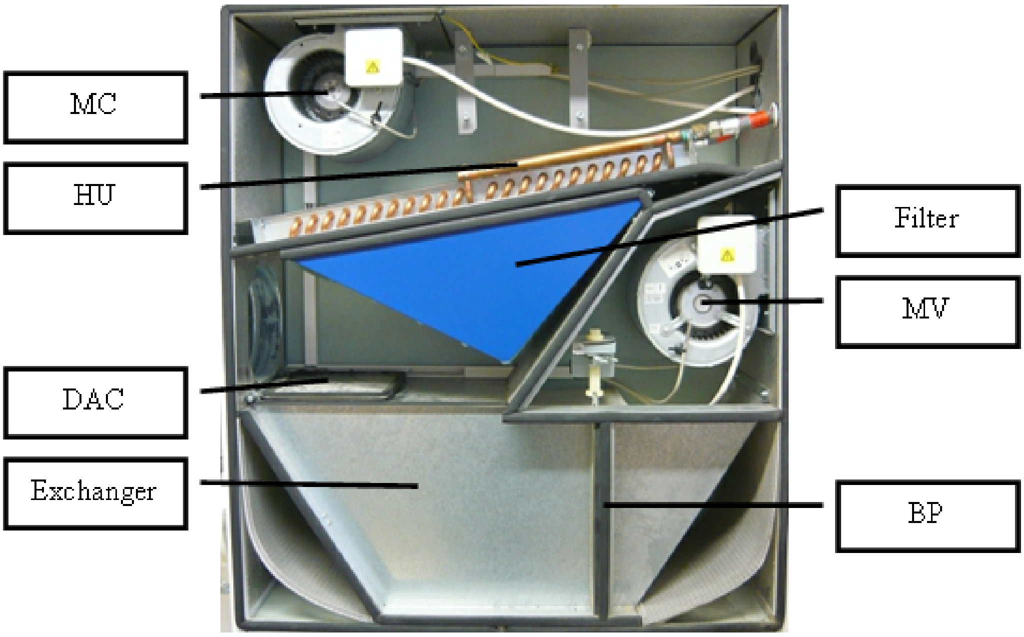


**Figure 5: Components of the recuperation unit**

In Table 3 the used sensors and their abbreviations are presented. These abbreviations are used in next chapters. The locations of the sensors are written in the third column of this table.

**Table 3: List of sensors of the recuperation unit**

| Abbreviation | Sensor | Location |
|---|---|---|
| T_MV | temperature sensor Ni1000 | ventilator of the waste air |
| T_MC | temperature sensor Ni1000 | ventilator of the circulation |
| T_INT | temperature sensor Ni1000 | inside the room |
| T_OUT | temperature sensor Ni1000 | outside |
| S1 | NDIR sensor AS$CO_2$-GD | in the circulation pipe |
| S2 | NDIR sensor AS$CO_2$-GD | in the circulation pipe |

In Figure 6 the scheme 30/1 of the recuperation unit used in this thesis is viewed. $C_1$ is the input of the circulation air into the recuperation unit. $C_2$ is the output of the circulation air from the recuperation unit. $i_1$ is the part of the circulation air which gives the thermal energy to the input of the fresh air $e_1$ in the exchanger and after that it leaves the recuperation unit like waste air $i_2$. The behaviour of air flows is described in section 2.3.

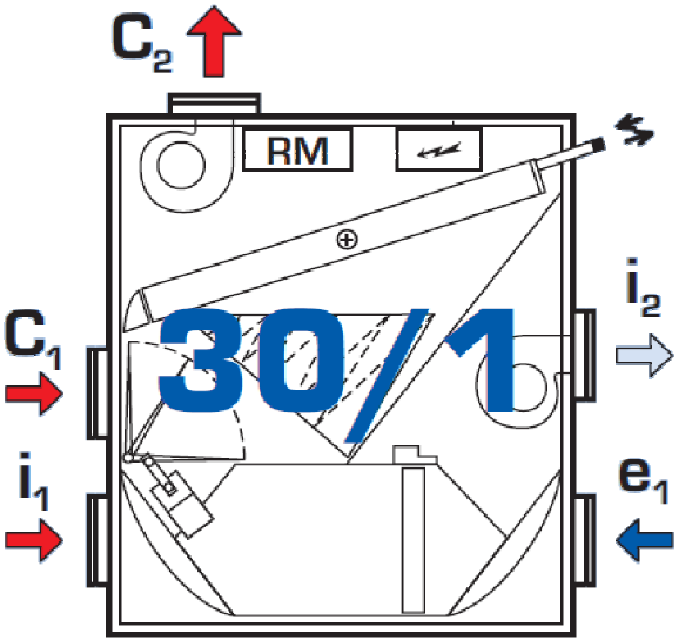


**Figure 6: Scheme of the ATREA DUPLEX RB type 30/1 [19]**

## 2.3 Working modes of the recuperation unit

The recuperation unit has five working modes. Working modes of the recuperation unit depend on season of the year, because there are differences of the atmospheric pressure between indoor and outdoor of the building in each season of the year. The effect of the natural balancing of the atmospheric pressure is used in some modes and it decreases operating costs of the recuperation unit, because ventilators need not to be working.

### 2.3.1 Balanced pressure ventilation mode

Balanced pressure ventilation mode with air flow through exchanger or through by-pass is used in transient seasons when the season without heating is ending and the heating season is starting or the other way around. So it is spring or autumn. This mode is without circulation. The damper of the circulation is closed. Both of the ventilators are working (see reference [19]). In Figure 7 the principle of the balanced pressure ventilation mode is presented.

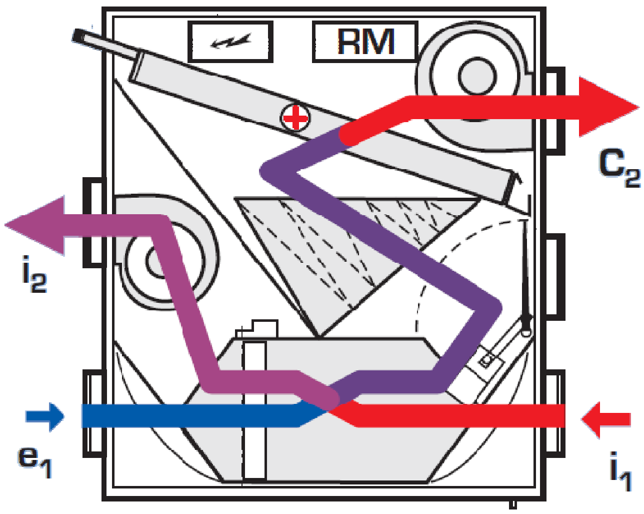


**Figure 7: Balanced pressure ventilation mode [19]**

### 2.3.2 Circulating heating and ventilating mode

Circulating heating and ventilating mode is used in the heating season. It is mainly the winter. Sometimes the heating season is from the end of the autumn to the start of the spring. This mode is with circulation. The damper of the circulation is half-opened, so it means that circulating air is mixed with the fresh air coming from the exchanger. Both of the ventilators are working (see reference [19]). In Figure 8 the principle of the circulating heating and ventilating mode is presented. The difference between Figure 8 and Figure 7 is that the damper of the circulation is half-open, so the circulation air is mixed with the fresh air which is coming from the exchanger, where gets thermal energy from the waste air.

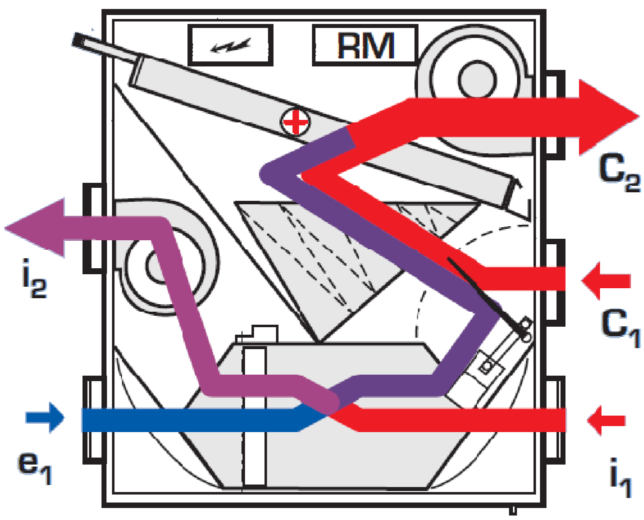


**Figure 8: Circulating heating and ventilating mode [19]**

### 2.3.3 Circulating heating mode with spasmodic ventilation

Circulating heating mode with spasmodic ventilation is the basic recommended mode. This mode is used mainly in the heating season. The ventilator of the circulation is working. The damper of the circulation is open. The ventilator of the waste air is stopped. But when the freshness of the air in the building decreases under the permissible level, the ventilator of the waste air is working and the damper of the circulation is half-opened, so it means that the fresh air from the exchanger is mixed with circulating air for a time needed to have a good freshness of the air (see section 2.3.2). This mode is realized for automatic control in this thesis (see reference [19]). In Figure 9 it is possible to see the circulating heating mode with spasmodic ventilation. The damper of the circulation is opened, so there is the circulating air. Figure 8 in section 2.3.2 presents ventilation, when the freshness of the air in the building decreases under the permissible level.

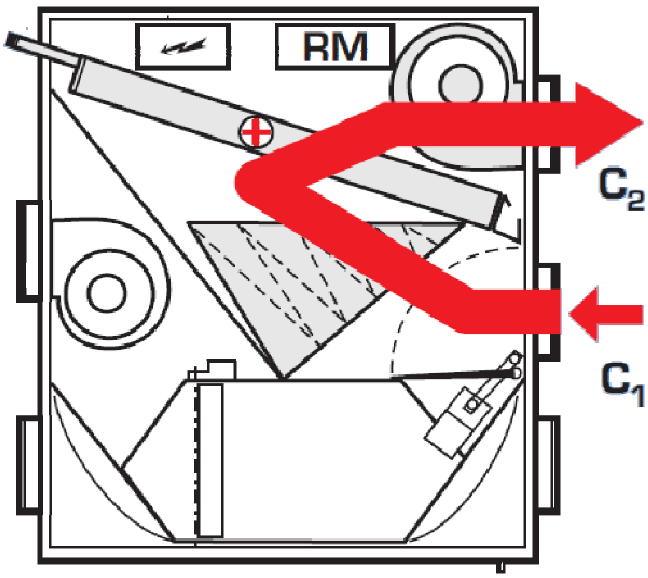


**Figure 9: Circulating heating mode with spasmodic ventilation [19]**

### 2.3.4 Underpressure ventilation mode

Underpressure ventilation mode is used in the season without heating. Waste air is underpressure sucked. There is a part-inflow of the fresh air through the unit. The ventilator of the circulation is stopped. The damper of the circulation is closed (see reference [19]). In Figure 10 the underpressure ventilation mode is presented.

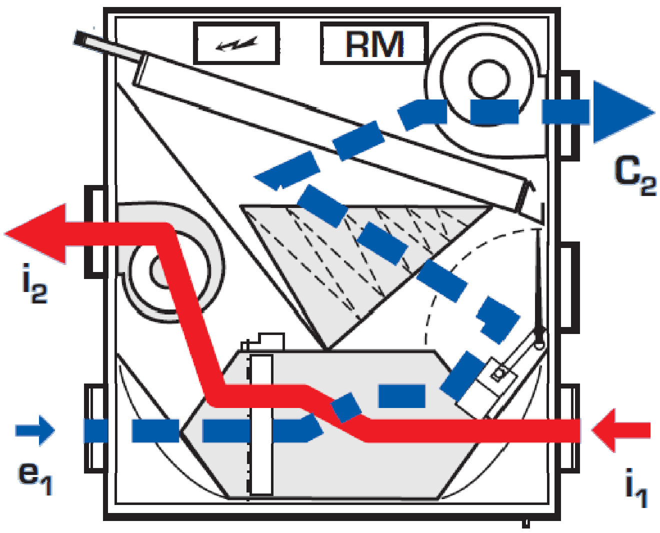


**Figure 10: Underpressure ventilation mode [19]**

### 2.3.5 Overpressure ventilation mode

Overpressure ventilation mode is used in the summer. The ventilator of the circulation is stopped. The damper of the circulation is closed. By-pass is open. The ventilator of the waste air is working, if it is needed (see reference [19]). In Figure 11 the overpressure ventilation mode is presented.

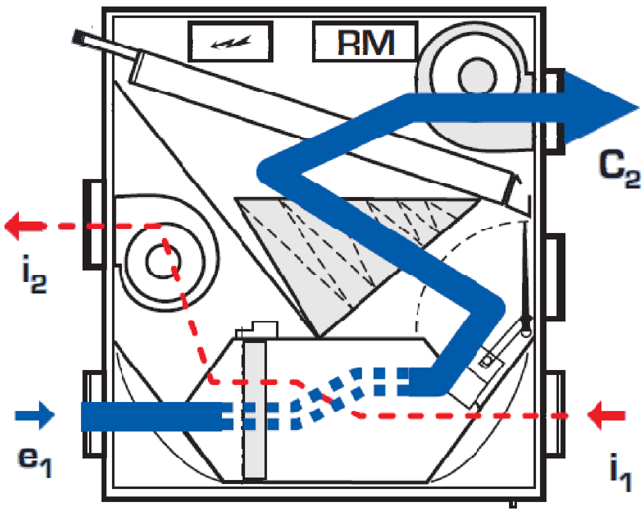


**Figure 11: Overpressure ventilation mode [19]**

# 3 The quality of the air in buildings

The quality of the air is a global topic around the world. The global trend is watching the pollution and decreasing the pollution of the air in the cities and industrial regions. We can say that the regions with heavy industry have higher level of the pollution. The main pollutants are carbon dioxide, carbon monoxide, sulphur dioxide and other gases which are mostly produced by the combustion in devices (for example combustion engines in cars). There are a lot of researches which found out relations between the air pollution and the health of population.

The quality of the air in buildings is mainly connected with the level of the carbon dioxide ($CO_2$), because it is product of breathing. The other pollutants are not produced in the building. The concentration of the carbon dioxide has influence on the comfort of people who are in the building. Too high concentration of the carbon dioxide makes people tired or it can cause the collapse of the human organism. So the concentration of the carbon dioxide is good measurable indicator of the freshness of the air in the building (for more information see references [2], [11], [13]).

Figure 12 is the graph of the composition of the atmosphere. The composition of the atmosphere approximately is: 78 % of the nitrogen, 21 % of the oxygen, 0.4 % of the water steam, 0.04 % of the carbon dioxide. Rare gases and etc. are the rest of this composition. The concentration of the carbon dioxide is 0.04 %, it is mostly measured in ppm units (parts per million), it means 400 ppm of the carbon dioxide in the atmosphere (see reference [13]).

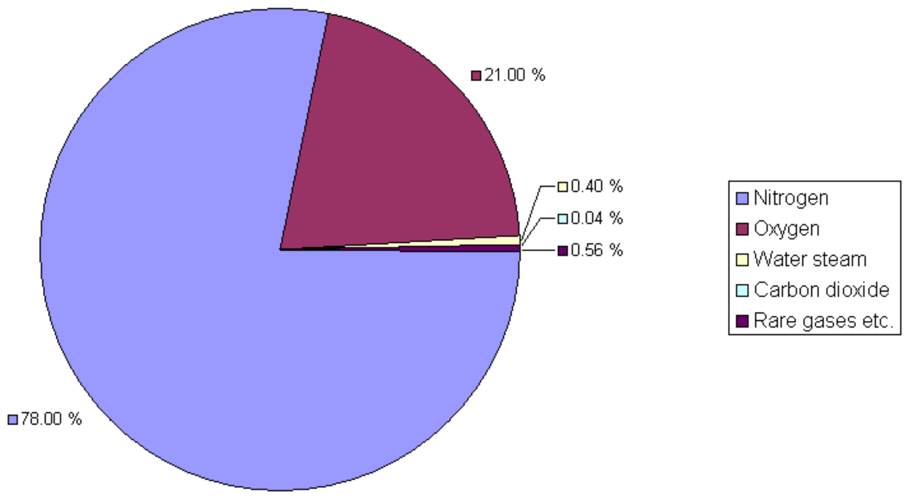


**Figure 12: Composition of the atmosphere [13]**

The concentration of the carbon dioxide is from 35000 ppm to 50000 ppm in the air which the body of the adult human is breathing out. It means that that the concentration of the $CO_2$ is increasing in closed room with people. It is possible to approximately find out, how many people are in the closed room (see reference [13]). Table 4 shows values of the $CO_2$ concentration and their description of the quality of the air.

**Table 4: $CO_2$ concentration and quality of the air [13]**

| $CO_2$ concentration [ppm] | Quality |
|---|---|
| 360 – 400 | atmospheric air, fresh air |
| 800 – 1000 | recommended level in objects |
| > 1000 | tiredness is increasing, attention is decreasing |
| 5000 | maximal level without health hazard |

## 3.1 Methods for measuring of the $CO_2$ concentration

There are several methods for measuring of the concentration of the carbon dioxide and other gases.

### 3.1.1 Non-Dispersive Infrared Radiation sensors

NDIR means Non-Dispersive Infrared Radiation. This method is based on absorption of specific wavelength of the infrared light which goes through the observed sample of the air. There is light detector that measures attenuation of radiation and transfers into the electrical signal. In Figure 13 the principle of the NDIR sensor is presented. This method is frequently used. These sensors are more accurate and stable, but the price of this type of device is higher than other types. NDIR sensors are also used in this thesis for watching of the $CO_2$ concentration. This type of sensors was chosen, because the accuracy is important for better identification of the number of people in object. In the case of this work I used two NDIR sensors ASCO$_2$-GD produced by Czech company Protronix s.r.o. For more information see references [11], [13], [21].

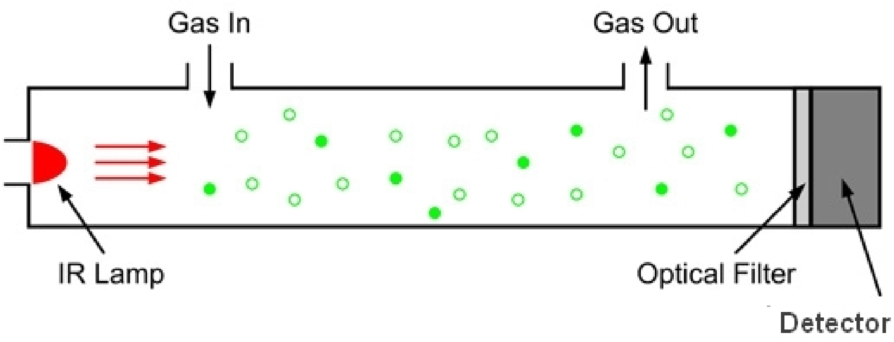


**Figure 13: NDIR sensor principle [10]**

### 3.1.2 Electrochemical sensors

Electrochemical sensors are composed of electrochemical cell with electrolyte. This cell is warmed up to working temperature with added heater. The chemical process on electrodes is the same like in the case of galvanic cell (for example batteries). This process is consuming the oxygen. The electrical power is generated on electrodes by this effect. It is possible to get the information about $CO_2$ concentration by the measuring the electrical power, which is generated by this electrochemical process. These sensors have high sensitivity. The sensors are cheaper than NDIR sensors, but working life is shorter and the accuracy is less. On the other hand, electrochemical sensors are still suitable for the air-conditioning industry (see reference [13]). In Figure 14 the principle of the electrochemical sensor is presented.

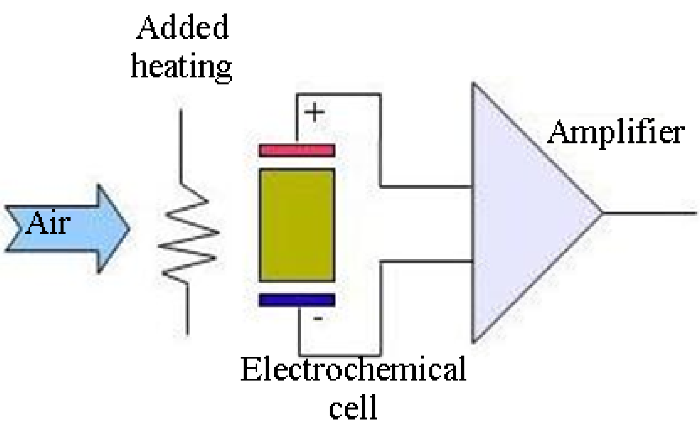


**Figure 14: Electrochemical sensor principle [13]**

### 3.1.3 Electroacoustic sensors

Electroacoustic sensors sense the change of the frequency of the ultrasound. There is a relation between the $CO_2$ concentration and the change of the ultrasound frequency. The advantage of these sensors is long stability without recalibration (see reference [13]). In Figure 15 the principle of the electroacoustic sensor is presented.

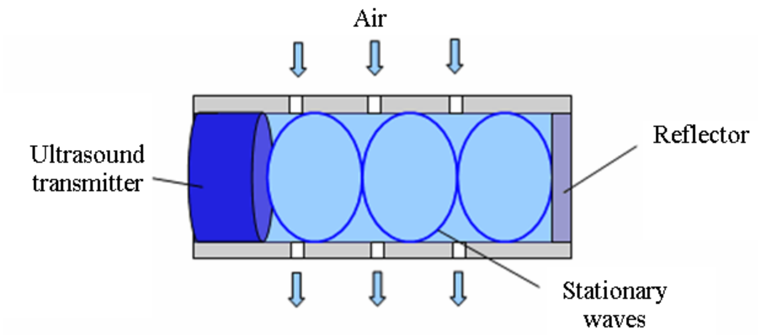


**Figure 15: Electroacoustic sensor principle [13]**

# 4 Design of the electrical switchboard

In this part components installed into electrical switchboard will be presented. These components are:

- Variable-frequency drive
- Power supply
- Residual-current device
- Temperature sensor
- Non-dispersive infrared radiation sensor

The design of this is also described in semestral project (see [22]), which is written by author of this thesis. The assembling was realised during the semestral project and this diploma thesis, which is extension of the semestral project.

The scheme of the electric circuit is in the attachment. The PLC system TECOMAT FOXTROT CP-1018 will be described in the separate chapter.

## 4.1 Variable-frequency drive Mitsubishi D700

It is for controlling of rotation speed of the asynchronous electric motors. The control of the rotation speed optimizes the process (of the circulation in the case of this thesis). It decreases operating costs. The variable-frequency drive (VFD) is used for changing of the frequency of the electric current. Variable-frequency drives are also known as adjustable-frequency drives (AFD), variable-speed drives (VSD), AC drives, microdrives or inverter drives. The variable-frequency drive has 3 main parts: rectifier, DC link and inverter. The rectifier rectifies alternating voltage to pulsing direct voltage. This pulsing direct voltage is stabilized and smoothed by the DC link and after it is passed to the inverter. The inverter generates alternating voltage with frequency what is proportional to wanted rotation speed of the electric motor. The variable-frequency drive Mitsubishi D700 (see Attachment 2) is suitable for driving one phase asynchronous motor up to 2.2 kW, so there are two devices used for driving the ventilator of the circulation and the ventilator of the waste air (see reference [5]). Figure 16 represents the block scheme of the variable-frequency drive.

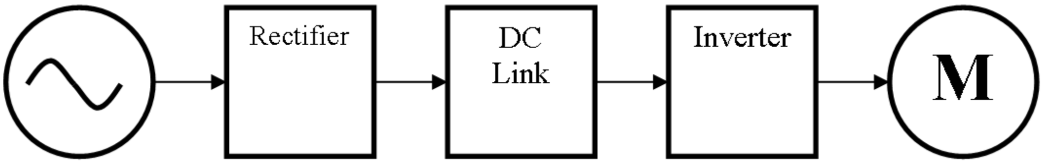


**Figure 16: Block scheme of VFD**

Table 5 shows basic specification of the variable-frequency drive Mitsubishi D700.

**Table 5: VFD Mitsubishi D700 specification [5]**

| | |
|---|---|
| Power supply (50/60Hz) | 200–240 V |
| Output range | 0.1 kW–2.2 kW |
| Protective structure | IP20 |
| Output frequency | 0.2–400 Hz |

## 4.2 Power supply 24 V DC Mean Well MDR-60-24

Power supply 24 V DC Mean Well MDR-60-24 is used for power supplying (see Attachment 2) of the PLC, NDIR sensors and temperature sensors. These electric loads have not higher consumption than 60 W, so this power supply is suitable (see reference [4]). Table 6 gives basic properties of the power supply 24 V DC Mean Well MDR-60-24.

**Table 6: Properties of power supply 24 V DC Mean Well MDR-60-24 [4]**

| | |
|---|---|
| Input VAC | from 85 V to 264 V |
| Input Frequency | from 47 Hz to 63 Hz |
| Output Voltage | 24 V DC |
| Output Current | 2.5 A |
| Operating Temperature | from – 20 °C to 55 °C |
| H/W/D | 9/4/10 cm |

## 4.3 Residual-current device OEZ OLFI C10

Residual-current device (RCD) disconnects the electrical circuit when part of incoming current is lost by the accident. This accident can be caused by broken isolation or touch of human. Basic component of this device is differential transformer. This transformer watches difference between input and output current of the electrical circuit, what should be equal 0 A. When the difference is more than 30 mA (in our case) the electrical circuit is disconnected. So it means that residual-current device is safety element in the electrical circuit. The using of the safety elements in electrical circuits is regulated by standards. The residual-current device

OEZ OLFI C10 was used in this thesis (see Attachment 2). This type is produced by the Czech company OEZ s.r.o., which it is a member of Siemens group (see reference [6]).

## 4.4 Temperature sensor Ni1000

Temperature sensor Ni1000 is a resistance temperature sensor. It means that it uses temperature properties of metal. In this case the metal medium is a nickel. There is a relation between resistance of the sensor and temperature. The range of measurement is from – 70 °C to 200 °C. This type of sensors has good accuracy and reaction on the change of temperature. Next advantage is small size (see reference [9] for more information).

## 4.5 Non-Dispersive Infrared Radiation sensor ASCO$_2$-GD

The principle of the Non-Dispersive Infrared Radiation (NDIR) sensor was explained before in section 3.1.1. The NDIR sensor of the $CO_2$ concentration ASCO$_2$-GD produced by the Czech company Protoronix s.r.o. is used in this thesis. Chosen sensor has good accuracy and it is designated for measuring in air-conditioning pipes. The specifications of this sensor are presented bellow (see reference [11] for more information). The picture of the NDIR sensor ASCO$_2$-GD is in the attachment 1. Table 7 presents basic parameters of the NDIR sensor ASCO$_2$-GD.

**Table 7: Parameters of the NDIR sensor ASCO$_2$-GD [11]**

| Parameter | Value | Unit |
|---|---|---|
| Voltage input DC | 14–40 | V |
| Voltage input AC 50/60 Hz | 18–32 | V |
| Voltage output DC | 0–10 | V |
| Measurement range | 0–2000 | Ppm |
| Measurement resolution | 20 | Ppm |

Table 8 shows values of the output voltage of the NDIR sensor ASCO$_2$-GD. This output voltage depends on $CO_2$ concentration.

**Table 8: Output voltage and $CO_2$ concentration of the sensor ASCO$_2$-GD [11]**

| Concentration $CO_2$ [ppm] | Voltage output 0–10 V [V] |
|---|---|
| 400 | 2.0 |
| 800 | 4.0 |
| 1200 | 6.0 |
| 1600 | 8.0 |
| 2000 | 10.0 |

Figure 17 presents the graph of the linear dependence of the output voltage of the NDIR sensor ASC$O_2$-GD on the $CO_2$ concentration.

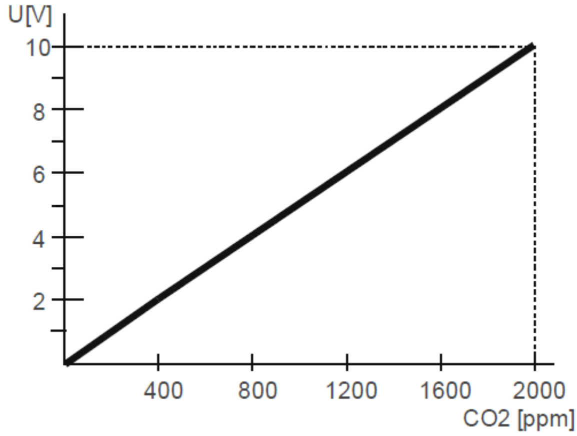


**Figure 17: Output voltage and $CO_2$ concentration of the sensor ASC$O_2$-GD [11]**

In this realization it is necessary to modify the range of the output voltage of the sensor, because there is no input port into the used PLC TECOMAT FOXTROT CP-1018 with range 0–10 V, there are only input ports with range 0–1 V or 0–2 V. The modification is made by voltage divider. The equation (1) describes how to compute modified voltage ($U_m$) of the voltage divider. The output voltage of the NDIR sensor (U) is modified. Resistor (R1) is divided as it is shown in the Figure 18. Rc represents all of resistors in the voltage divider.

$$Um = U \cdot \frac{R1}{Rc} \tag{1}$$

Figure 18 shows the realization with five 1 kΩ resistors. This realization is used in case of this thesis. It is possible to use other resistors, but the equation (1) must be valid.

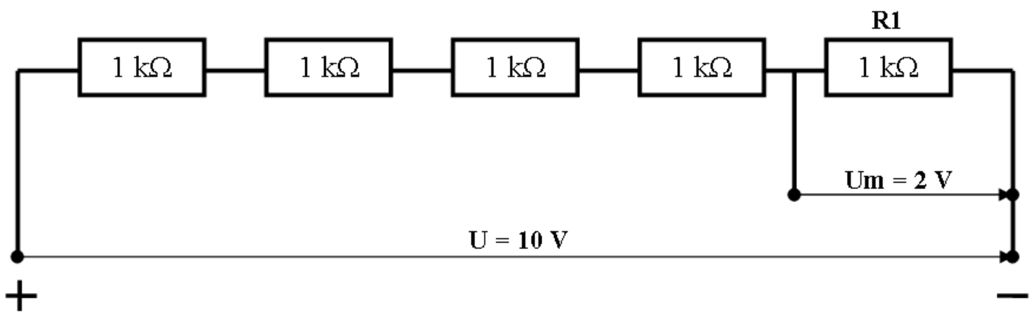


**Figure 18: The voltage divider scheme**

# 5 PLC TECOMAT FOXTROT CP-1018

Programmable logic controller (PLC) is the digital electronic system for controlling machines and processes in industrial environment. PLC works with digital and analogue inputs and controls digital and analogue outputs. Controlling algorithm of the PLC is written like a sequence instructions in memory of user program. The central unit reads this memory and processes instructions one by one. When all of the instructions are done, the central unit makes actualization of the output variables for peripheral modules and makes actualization of the input variables from peripheral modules. This process called cycle of the program and it still repeats. Used PLC Tecomat Foxtrot CP-1018 (see Figure 19) is made by Czech company Teco a.s. This PLC is suitable for automation of buildings (intelligent houses), where this PLC can control the recuperation unit. Presented recuperation unit ATREA DUPLEX RB is usually regulated by controller CP 05 RD, which is produced also by ATREA Company. This controller is designated only for regulating the recuperation units, whereas Tecomat Foxtrot CP-1018 can be extended for more tasks in the A-TK3 laboratory, for example intelligent house task can be realised (see reference [3], [19], [23]).

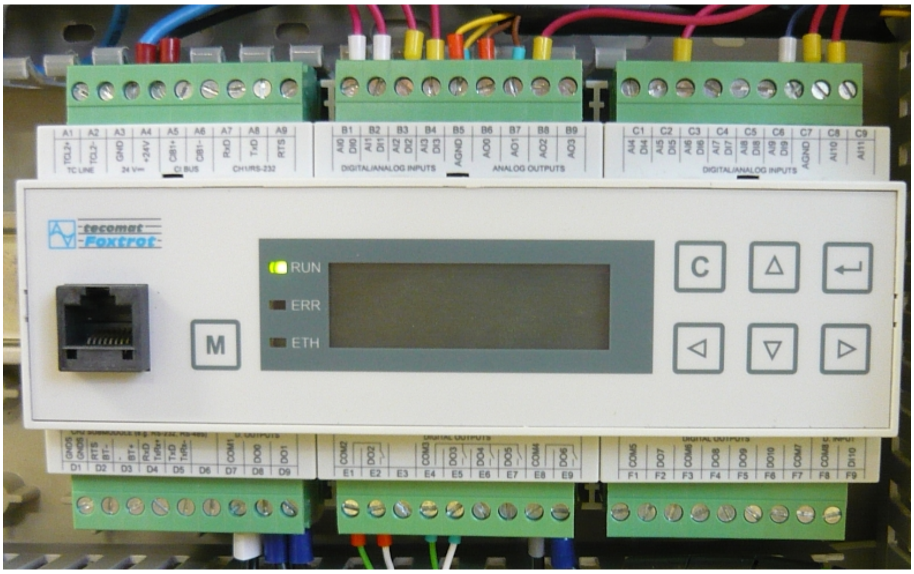


**Figure 19: PLC Tecomat Foxtrot CP-1018**

Table 9 presents used ports of the PLC Tecomat Foxtrot CP-1018 for the task of this thesis.

**Table 9: Used ports of the PLC Tecomat Foxtrot CP-1018 [23]**

| Connector | | | Connected device |
|---|---|---|---|
| A3 | GND | Ground | |
| A4 | +24V | Power | |
| B1 | AI0 | analogue input | T_MV |
| B2 | AI1 | analogue input | T_INT |
| B3 | AI2 | analogue input | T_OUT |
| B4 | AI3 | analogue input | T_MC |
| B5 | AGND | analog ground | |
| B6 | AO0 | analogue output | MC |
| B7 | AO1 | analogue output | MV |
| B8 | AO2 | analogue output | DAC |
| C7 | AGND | analogue ground | |
| C8 | AI10 | analogue input | S1 |
| C9 | AI11 | analogue input | S2 |
| D7 | COM1 | common wire of outputs DO0,DO1 | |
| D8 | DO0 | triac output | HU |
| D9 | DO1 | triac output | DAO |
| E1 | COM2 | neutral wire of output DO2 | |
| E2 | DO2 | relay output | MC_EN |
| E4 | COM3 | common wire of outputs DO3-DO5 | |
| E5 | DO3 | relay output | MV_EN |
| E8 | COM4 | neutral wire of output DO6 | |
| E9 | DO6 | relay output | BP |

## 5.1 Mosaic development environment

Mosaic is a development environment for creating and debugging programs for programmable logic controllers TECOMAT and TECOREG. It is produced by Czech company Teco a.s. since 2000. Mosaic meets the international standard IEC EN-61131-3 for programming PLC (see [3], [24]).

## 5.2 Program of the PLC

There are four programming languages which are possible to use for programming the PLC Tecomat Foxtrot CP-1018:

- LD – Ladder Diagram
- IL – Instruction List
- FBD – Function Block Diagram

- ST – Structured Text.

In this case the ST language is used, because it is higher programming language based on C and Pascal language. Other programming languages could be confusing with increasing complexity of the program. It is possible to use all techniques of the higher programming language with ST language like conditions, cycles, etc. See references [23], [24] for more information.

### 5.2.1 Automatic mode

The automatic mode is designed according to circulating heating mode with spasmodic ventilation (see section 2.3.3). In the beginning of the program the ventilator of the circulation is working (MC:=10.0;) and the damper of the circulation is opened (DAC:=0.0;). When the reference temperature (selected by user) is higher than temperature inside (T_REF>T_INT), the Boolean variable *tok* is false and the heating unit is working (HU:=1;). The heating unit is turned off, when the Boolean variable *tok* is true, it means that reference temperature is lower then temperature inside + 1 °C (T_REF<T_INT+1.0;). When the $CO_2$ concentration inside is higher than 1000 ppm (S2P>1000), the Boolean variable *sok* is false the damper out is opened (DAO:=0;), the damper of the circulation is half-opened (DAC:=5.0;) and the ventilator of the waste air is working (MV:=10.0;). In this moment, part of the circulating air is mixed with the fresh air and part of the circulating air leaves the building with exchange of thermal energy. When the $CO_2$ concentration inside is lower than 600 ppm (S2P<600), the Boolean variable *sok* is true, then the damper out is closed (DAO:=1;), the damper of the circulation is opened (DAC:=0.0;) and the ventilator of the waste air is not working (MV:=0.0;). Figure 20 is a flow diagram visualising the automatic mode.

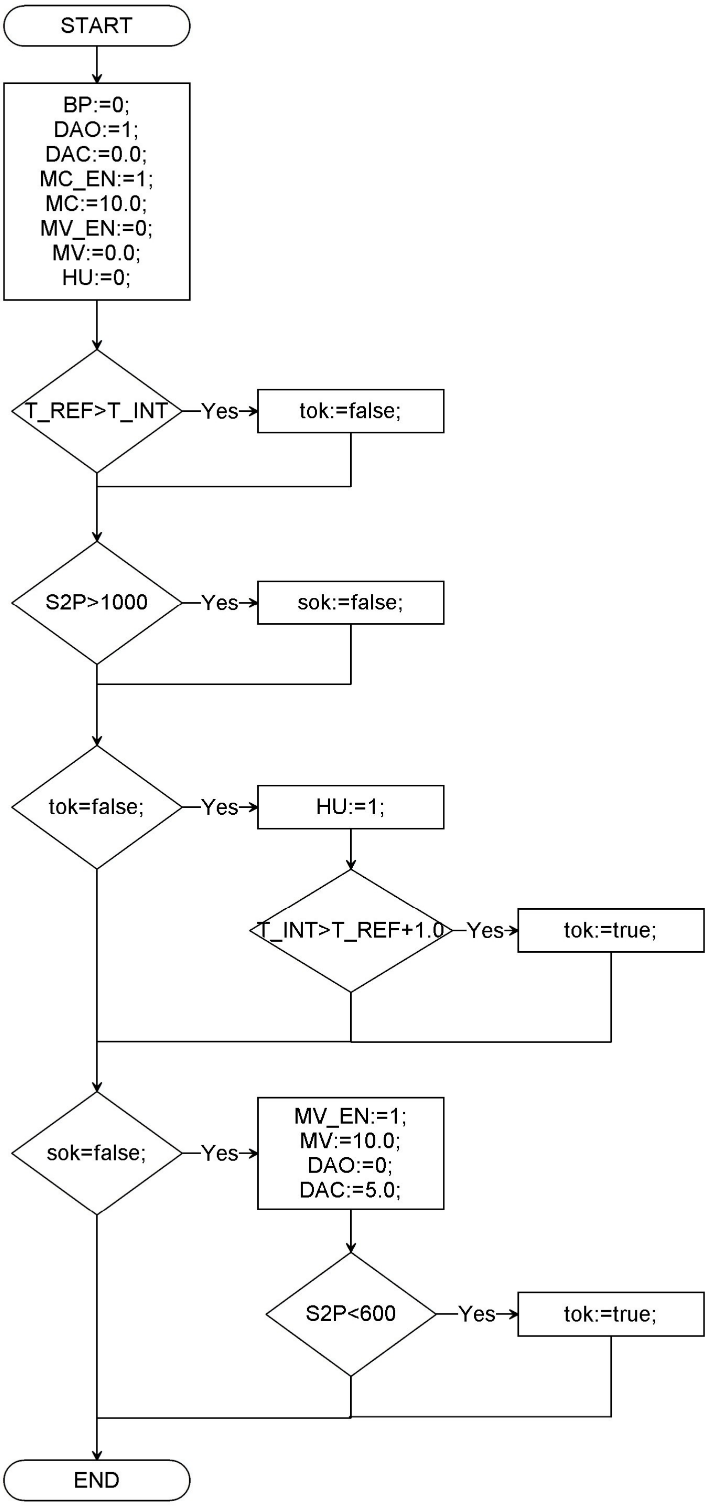


**Figure 20: Diagram of the automatic mode**

### 5.2.2 Defining of variables

```
VAR_GLOBAL
  T_OUT    at r0_p3_AI2.ENG;    //temperature sensor Ni1000 OUTSIDE
  T_MC     at r0_p3_AI3.ENG;    //temperature sensor Ni1000 MC
  T_MV     at r0_p3_AI0.ENG;    //temperature sensor Ni1000 MV
  T_INT    at r0_p3_AI1.ENG;    //temperature sensor Ni1000 INSIDE
  MC       at r0_p3_AO0.ENG;    //ventilator of the circulation
```

```
    MC_EN    at r0_p3_DO.DO2;
    MV       at r0_p3_AO1.ENG;    //ventilator of the waste air
    MV_EN    at r0_p3_DO.DO3;
    DAC      at r0_p3_AO2.ENG;    //damper of the circulation
    BP       at r0_p3_DO.DO6;     //by-pass
    HU       at r0_p3_DO.DO0;     //heating unit
    DAO      at r0_p3_DO.DO1;     //damper out
    S1       at r0_p3_AI10.ENG;   //NDIR sensor ASCO2-GD 1
    S2       at r0_p3_AI11.ENG;   //NDIR sensor ASCO2-GD 2
    MCBar,MVBar,KBar :REAL;    //variables for visualization
    MCPlus,MCMinus   :BOOL;    //buttons of control panel
    MVPlus,MVMinus   :BOOL;    //buttons of control panel
    KPlus,KMinus     :BOOL;    //buttons of control panel
    automat          :BOOL;    //button of automatic mode
    T_REF            :REAL;    //temperature set point
    S1P              :REAL;    //variable for visualization in ppm
    S2P              :REAL;    //variable for visualization in ppm
    contrI1,contrO1  :BOOL;    //output and input of timer1
    contrI2,contrO2  :BOOL;    //output and input of timer1
    contrI3,contrO3  :BOOL;    //output and input of timer1
  END_VAR
```

### 5.2.3 Program of the automatic mode

In this section the program of the automatic mode, which is described in section 5.2.1, is presented in ST language.

```
//initialization
      BP:=0;
      DAO:=1;
      DAC:=0.0;
      MC_EN:=1;
      MC:=10.0;
      MV_EN:=0;
      MV:=0.0;
      HU:=0;

//variables for visualization
      MCBar:=MC*10.0;
      MVBar:=MV*10.0;
      DACBar:=DAC*10.0;

//condition reference temperature > temperature inside
      if T_REF>T_INT then tok:=false; end_if;

//condition CO2 concentration > 1000 ppm
      if S2P>1000.0 then sok:=false; end_if;

//condition temperature is not ok
      if tok=false then
         HU:=1;         //heating unit is working

      //condition temperature inside > reference temperature + 1
         if T_INT>T_REF+1.0 then
            tok:=true; //temperature is ok
         end_if;
      end_if;
```

```
//condition CO2 concentration is not ok
      if sok=false then
         MV_EN:=1;
         MV:=10.0;      //ventilator of the waste air is working
         DAO:=0;        //damper out is open
         DAC:=5.0;      //damper of the circulation is half-open

      //condition CO2 concentration < 600 ppm
         if S2P<600.0 then
            sok:=true; //CO2 concentration is ok
         end_if;
      end_if;
```

### 5.2.4 Mosaic WebMaker

One part of the development environment Mosaic is called WebMaker. The WebMaker is used for realising web pages for Teco PLC systems with web server. It can be also used for making the control panel where control buttons and visualization of measured variables are realised. It is not necessary to have system with web server for the visualization. For using of the web server function it is necessary to insert the memory card into the PLC, because web pages are saved on it (see reference [25] for more information).

In the Figure 21 it is shown the realization of the control panel by the Mosaic WebMaker. In the first row the ventilator of the circulation (MC) control, the ventilator of the waste air (MV) control and the damper of the circulation (DAC) control are presented. When the device is working, it is indicated by the green light. The performance of the device is visualised by the green column and by the number between arrows. The arrows are for controlling of the device performance. It is possible to see temperature of the air which flows into both ventilators (T_MC and T_MV). In the second row there are three buttons for controlling of the damper outside (DAO), the by-pass (BP) and the heating unit (HU). The fourth button is used for turning automatic mode on. On the right side, there is a field, where user can assign the reference temperature (T_REF) for automatic mode. All the buttons in this row are also indicated by green lights. In the bottom of the control panel there is information about the temperature inside (T_INT), temperature outside (T_OUT) and $CO_2$ concentration (from NDIR sensors S1 and S2).

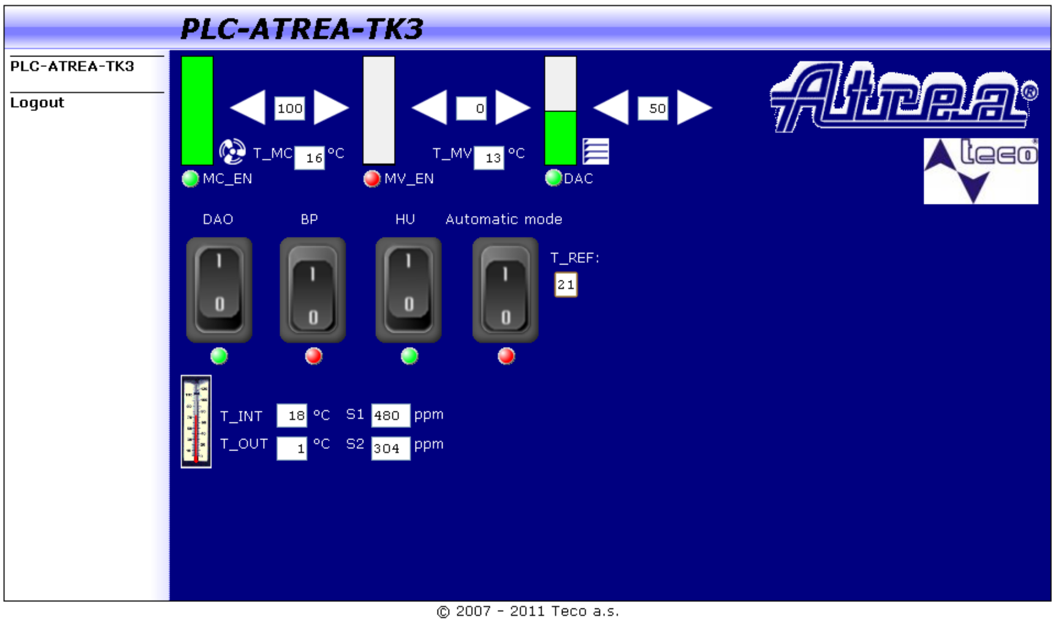


**Figure 21: Control panel realised in Mosaic WebMaker**

### 5.2.5 Datalogger

The Datalogger is a tool for automatic saving data and events of the PLC Tecomat. Records are saved to the memory card which must be a component of the PLC system. Files are saved in CSV format (Comma-Separated Values). This format can be easily processed by usual tab or database editors like Microsoft Excel, LibreOffice Calc, etc. (see [26]). In this thesis the Datalogger is used for recording data from NDIR sensor of $CO_2$ concentration which are analysed in section 6.3.

# 6 Identification of the number of people

This chapter presents the problem of the identification of the number of people in the object just based on the $CO_2$ concentration in the air. The measurement was taken in the A-TK3 laboratory of Technical University of Liberec and results are evaluated in this chapter.

## 6.1 Physiology of the human breathing

Processes in the human body are possible to approximately describe like a package of the physical and biochemical processes. These processes are presented in physiologic science. The physiology of the human breathing is a part of physiology of the human body. We can see differences among individuals. Everybody has different physiological parameters. It means that each human is unique. It is the same with physiological parameters of the human breathing. This fact brings inaccuracy to the identification of the number of people which is based only on $CO_2$ concentration in the air. There are several physiological parameters of the human breathing which have influence on identification of the number of people.

One of them is a *volume* of the lungs. Children have smaller volume of the lungs than adults. Women have different volume of the lungs than men. Sportsmen have usually bigger volume of the lungs than others. It is said that professional divers have the biggest volume of the lungs.

Next one is the *intensity* of the breathing. This physiological parameter mainly depends on physical and psychical load. When the person is upset, excited or somehow stressed, this person has higher intensity of the breathing than in normal state. When the person is doing some activity like walking, running or doing a sport, this person has higher intensity of the breathing than normally for example when is sitting.

The other physiological parameter of the human breathing is a *consumption of the oxygen* of the one inhalation or the $CO_2$ concentration of the exhalation. This parameter is connected with parameters presented before in this chapter and with the others physiologic parameters.

Physiologic parameters depend on characteristic of individual person. Basic characteristics are height, weight, age, sex. Physiologic parameters also depend on environment, where the person lives and on live style. In Table 10 basic physiological parameters of the human breathing are presented (see reference [15] for more information).

**Table 10: Basic physiological parameters of the human breathing [15]**

| Physiological parameters | |
|---|---|
| Average volume of air per breath | 0.5 $dm^3$ |
| Average number of breaths per minute | 15 – 20 |
| Average $CO_2$ concentration of exhaled air | 35000 – 50000 ppm |

## 6.2 Model

Consider that we have perfectly isolated space with volume of the air 420 $m^3$. This volume is the same in the A-TK3 laboratory, where the real measurement were realised. The initial $CO_2$ concentration of this space is 500 ppm. Then consider that 27 people are in this space. This number was chosen, because 27 students were in the A-TK3 laboratory, when main measuring were realised. Their average volume of air per breath is 0.5 $dm^3$. Their average number of breath per minute is 17.5. Their average $CO_2$ concentration of exhaled air is 42500 ppm (see section 6.1).

In the graph in Figure 22 is progress of the $CO_2$ concentration of the model in time of the 90 minutes. It is a linear process described by equation (2).

$$y = 23.625\,x + 500 \tag{2}$$

The constant of equation (2) is an initial value of the $CO_2$ concentration. In the time 90 minutes the $CO_2$ concentration is 2626 ppm. This concentration is higher than permissible level 1000 ppm. This model shows, how it should look, when 27 students with same physiological parameters are 90 minutes in A-TK3 laboratory, which is perfectly isolated, without other influences.

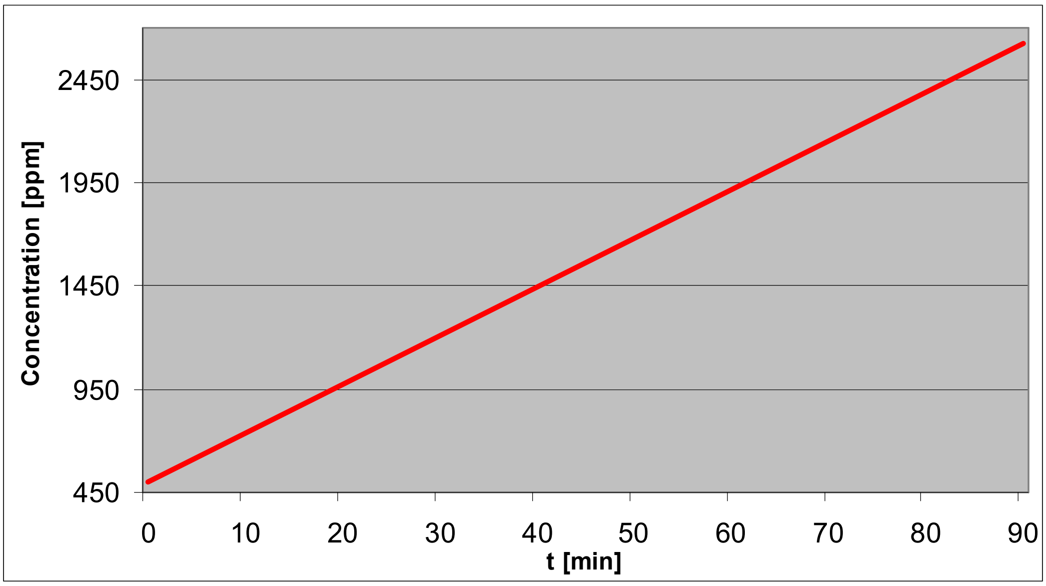


**Figure 22: Graph of the $CO_2$ concentration of the model**

## 6.3 Real measurement in A-TK3 laboratory

In section 6.2 the model of the $CO_2$ concentration progress is presented. Of course A-TK3 laboratory is not so perfectly isolated, so it is awaited influence of the air infiltrating from outdoor of the laboratory. It must be also expected that students have not same physiological parameters. Location of the recuperation unit, pipes and used NDIR sensors in A-TK3 laboratory is possible to see in Attachment 3.

In the graph in Figure 23 the progress of the $CO_2$ concentration is shown (blue line in this graph). The data were measured on Monday in 8$^{th}$ April 2013 from 8:50 AM to 10:20 AM. In this time there were almost the same conditions like in the model presented in section 6.2. There were 27 people for 90 minutes in A-TK3 laboratory, which has volume of the air 420 m$^3$. Values of the $CO_2$ concentration were written by Datalogger each 5 seconds.

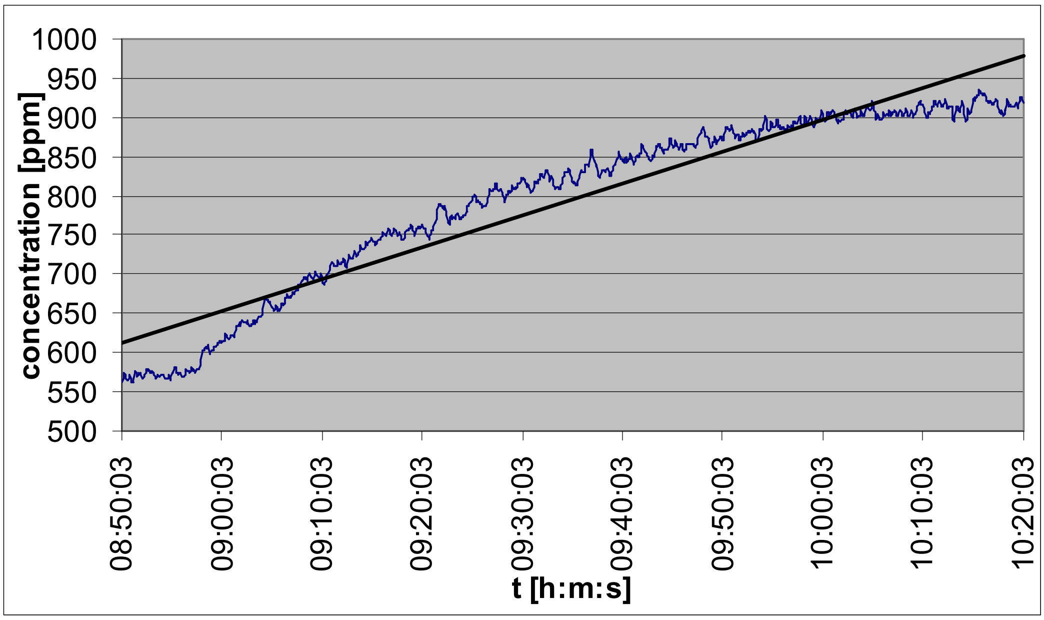


**Figure 23: Graph of the measurement**

In the graph it is possible to see that the presence of people was found out almost 10 minutes after they enter in to the laboratory. The progress is not linear. When the linear regression is applied (black line in the graph) then equation (3) of this progress with value of the reliability 91.26 % is given.

$$y = 4.086\,x + 611 \qquad (3)$$

This equation is different from equation presented in section 6.2. It is possible to say that this difference is caused by differential physiological parameters of people and by air infiltration from outdoor. Probably, the heavier carbon dioxide, which is holding closer to ground, has also influence on this progress. The results of the measurements which were obtained each Monday in April 2013 are almost same with small differences. It means that influences are variable. The progress in the graph reminds function of the first order. Probably it is possible to get more accurate model of the situation ($CO_2$ concentration with influences), when it is described by differential equations.

When these measurements are compared with other measurements when the number of students was different in the A-TK3 laboratory, it is possible to see that the dynamics of the $CO_2$ concentration is slower when the number of students is lower than 27 or faster when the number of students is higher than 27.

Figure 24 presents data measured during the $8^{th}$ April 2013. At beginning of the graph $CO_2$ concentration of empty room is viewed. Dynamics described before starts at 8:50. Then (at 10:20) some students leaves A-TK3 laboratory and the rest of students had next lesson.

$CO_2$ concentration is still increasing but the dynamics is not so fast because the number of students is lower (20 students). When $CO_2$ concentration crossed the level 1000 ppm, it is possible to see fast decrease of the concentration. The number of students is the same, but probably somebody opened windows. At 14:20 the lesson with 17 students starts, it can be said, than dynamics of $CO_2$ concentration is similar to the dynamics, when 20 students were in laboratory. This lesson was ended at 16:00. After that, the concentration was slowly decreasing. It was caused by outdoor influence.

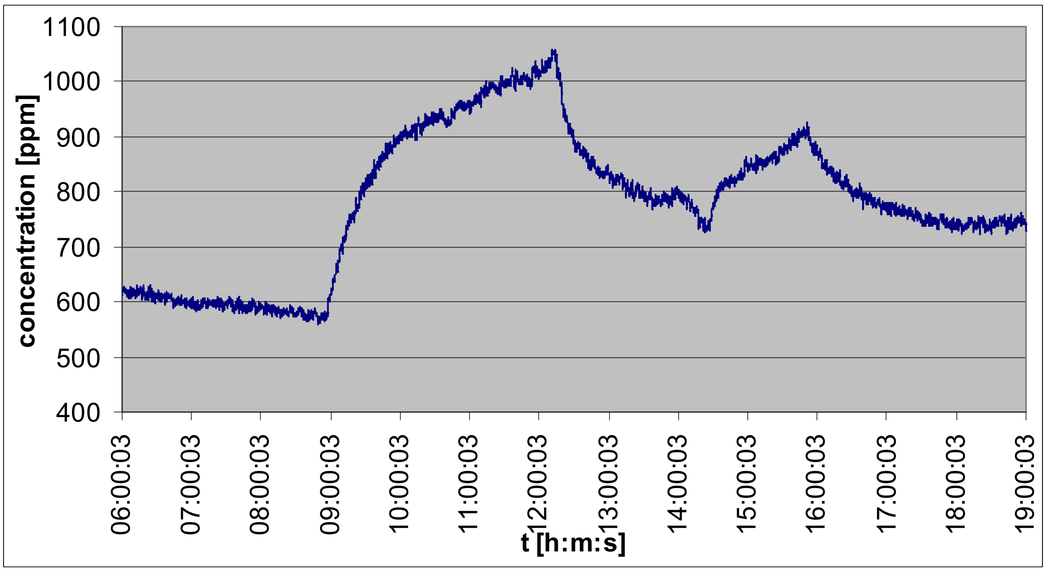


**Figure 24: Graph of the measurement of the day**

It can be said that approximate number of people in the room is detectable in long time term for example 90 minutes, when the measurement is compared with reference measurements.

## 6.4 How to have more accurate and faster identification?

As it was said in previous part, it is possible find out approximate number of people in the room in long time term, but it is not so practical, because the number of people can change faster than onetime in 90 minutes. For having better and faster identification, it is needed to:

- Find out and describe (by differential equation) influence of outdoor air in detail
- Find out and describe (by differential equation) circulation of the air in object in detail
- Have an approximate physiology profile of visitors
- Have support sensors (for example sensor indicates, if window is open)

# Conclusion

In this diploma thesis it was explained, what the recuperation unit is, how it works, where this manner of the heating is mostly used. There are presented some companies, which produce recuperation units and extending their possibilities of using. The recuperation unit ATREA DUPLEX RB (installed in A-TK3 laboratory) is controlled by PLC Tecomat Foxtrot CP-1018. This PLC is suitable for this task, because it is designated for automation of buildings. There are presented support electronic devices for whole system and assembly scheme of the whole system. NDIR method was chosen from three mentioned methods of $CO_2$ concentration measuring. NDIR sensor was connected to the system. The system uses data from NDIR sensor for automatic control. The program of automatic control works based on knowledge about air quality in buildings. Circulating heating mode with spasmodic ventilation is used. The program was developed in Mosaic environment. Control panel of the system with web access was also made in Mosaic. The last part of this thesis explores if it is possible use the data from $CO_2$ concentration sensors for the identification of the number of people in object. The complexity of this problem is presented. Hints for better identification are given. Testing of the whole system and measuring of $CO_2$ concentration were realised in A-TK3 laboratory. Tasks of this diploma thesis are achieved.

This thesis can be a foundation for the next research in the field of air quality control in buildings, intelligent house control and identification of the number of people. One working mode (mostly used) is applied in this thesis, but there are the others modes, so the program presented in this thesis can be extended. The efficiency of the recuperation unit system can be observed.

The used PLC can be designed like a central unit for intelligent house control. Coordination between the recuperation unit and normal heating can be realised. Lights and sockets can be controlled, so it is possible achieve decreasing of the energy consumption and increasing so called light comfort. The PLC can be used like a system for the protection of property, so there can be detection of thieves and fire detection.

In the field of the identification of the number of people in object the possibilities for better accuracy can be developed and applied. The method how to set the identification system can be invented, if conditions are changed (for example: when we want use this system in another object).

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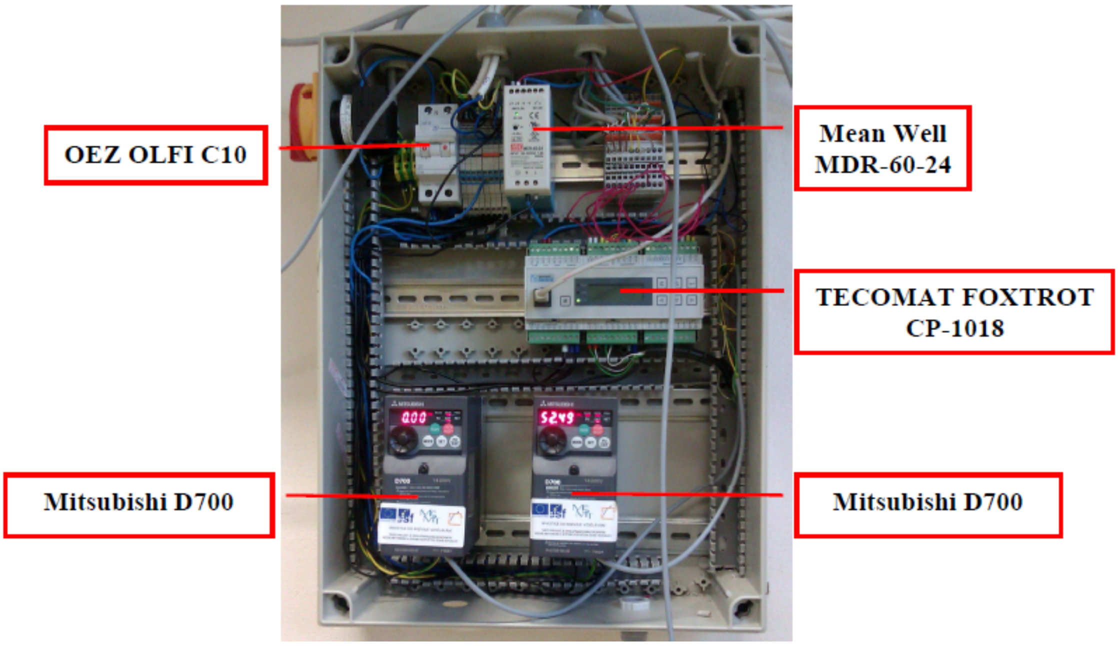
# Attachments

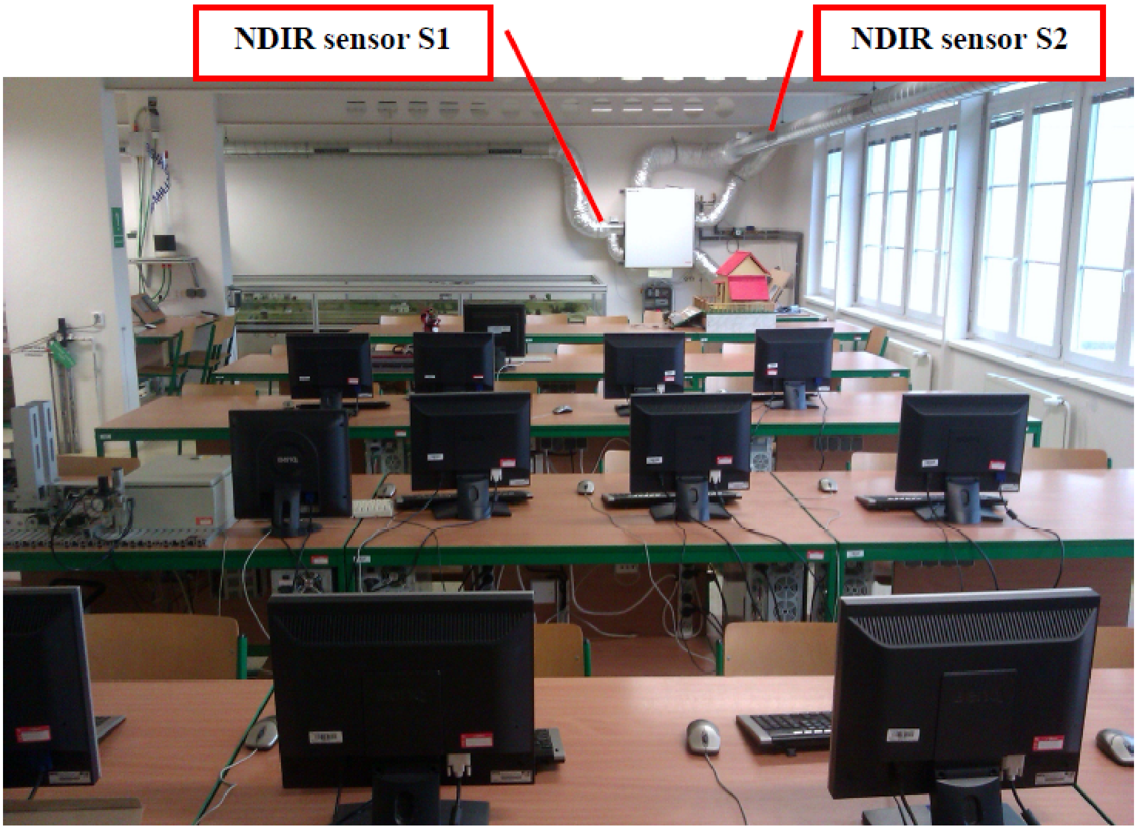
There is a scheme of the electric circuit on separate paper format A3.

### Attachment 1 – NDIR sensor AS $CO_2$-GD [11]

### Attachment 2 – Description of switchboard



## Attachment 3 –Location of NDIR sensors in A-TK3 laboratory




NDIR sensor S1 is placed in pipe where circulation air goes from the room into the recuperation unit. NDIR sensor S2 is placed in pipe where circulation air goes from the recuperation unit to the room.

# Content of the attached CD

- Diploma Thesis-Residential Heat Recovery Unit Controlled by PLC-J.Knop.pdf
- ATREA-scheme.pdf
- ATREA-MOSAIC-PROJECT.zip
- Measurements.zip